



Recovery of metals from spent lithium-ion battery leach solutions with a mixed solvent extractant system

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ABSTRACT

A mixed extractant system has been developed for the separation and purification of cobalt and lithium from spent lithium-ion battery leach solutions. The addition of Acorga M5640 to the Ionquest 801 organic solution generated a significant pH isotherm shift for copper with a ΔpH_{50} value of 3.45. As a result, the separation of iron(III), copper and aluminium from cobalt, nickel and lithium could easily be realised with the mixed extractant system.

The McCabe–Thiele diagrams at an A/O ratio of 2:1 and pH 4.0 showed that three theoretical stages are needed for the extraction of iron, copper and aluminium. The extraction kinetics of iron(III) and copper was rapid, but the extraction kinetics of aluminium was slow. With the increase of temperature from room temperature to 40 °C, the aluminium extraction kinetics increased substantially. It is therefore recommended that the metal extraction should be carried out at 40 °C. The stripping kinetics of aluminium and copper was rapid, but iron cannot be stripped effectively. Thus an organic bleed may be required to remove the iron with higher acid concentration in the strip solution. It is proposed that in the mixed organic system, Ionquest 801 played a role of extractant and Acorga M5640 a synergist for copper extraction.

A process flowsheet is proposed for recovering cobalt and lithium from spent lithium-ion battery leach solutions using the mixed Ionquest 801 and Acorga M5640 system in the first solvent extraction circuit, and Cyanex 272 in the second solvent extraction circuit. The advantage of this process is that pure cobalt and lithium products could be obtained.

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1. Introduction

The growth in the use of portable equipment such as cellular phones, notebook computers, video cameras, etc. has greatly stimulated the production and consumption of portable batteries. The generation of metal-containing hazardous waste from spent batteries is an environmental concern, and their recycling will reduce the amount of waste sent to landfill and improve the utilisation of the world's metal resources.

Several processes for the recovery of cobalt and lithium from spent lithium-ion batteries have been developed (Zhang et al., 1998, 1999; Lee and Rhee, 2002; Kim et al., 2004; Nan et al., 2006). The leach solution normally contains large amount of cobalt and lithium and small amount of nickel, copper, aluminium and iron. A number of solvent extraction (SX) techniques have been used to recover valuable cobalt and lithium. Two extractants, D2EHPA (di-2-ethyl-hexyl phosphoric acid) and PC-88A (2-ethyl-hexyl-phosphonic acid mono-2-ethyl-hexyl ester) were tested for the separation of cobalt from lithium by Zhang et al. (1998, 1999). It was found that PC-88A performed better than D2EHPA. This process gives high selectivity of cobalt over lithium and high purity

metal products. However the research was carried out using a solution containing two metals only (cobalt and lithium). Saponified Cyanex 272 (Na-Cyanex 272) was also used for the separation of cobalt from lithium in sulphate solutions (Swain et al., 2006).

Nan et al. (2006) reported a process to recover metal values from a mixture of spent lithium-ion and nickel-metal hydride batteries. After dissolution of the inner materials of the spent batteries, the rare earths were precipitated as double salts by precipitation with a mixed NaOH and Na_2CO_3 solution. Copper was separated and purified by SX with Acorga M5640 (5-nonylsalicylaldoxime), the separation of cobalt from nickel and lithium was conducted using Cyanex 272 in the pH range of 5.1–5.3 and the further separation of nickel from lithium in the pH range of 6.3–6.5. For spent lithium-ion battery leach solutions containing cobalt, lithium, nickel, copper, iron, aluminium and nickel, a possible process flowsheet would be copper SX, iron and aluminium precipitation and then using SX to separate cobalt, nickel and lithium.

The separation of lithium from alkali and alkaline earth metals was investigated by a number of researchers using synergistic solvent extraction (SSX) technique. The use of SSX systems consisting of D2EHPA and M2EHPA (mono-2-ethyl-hexyl phosphoric acid) with TBP (tri-n-butylphosphate), respectively, to extract lithium from geothermal spring water consisting of Na^+ , K^+ , Mg^{2+} , and Ca^{2+} was reported by Hano et al. (1992). The extractant showed high selectivity for lithium

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and divalent metals over other monovalent metals in a pH range of 6.2–6.6. The separation of lithium from divalent metals is possible by selective stripping, as divalent metals have a stronger affinity to the extractant. The synergistic effect was proposed to be due to the replacement of solvated extractant (D2EHPA or M2EHPA) by TBP. Ishimori and Imura (2002) reported the synergistic selective extraction of Li^+ from alkali ions such as K^+ and Na^+ with 2-thenoyltrifluoroacetone and 1,10-phenanthroline derivatives. The maximum separation factor was found to be over 6600. These systems are not practical for spent lithium-ion battery solution as heavy metals were not tested. Moreover, the two new reagents are not commercially available.

An ion-exchange resin, Doex M4195 (former XFS 4195), was reported for the separation of copper, nickel and cobalt from iron and aluminium (Grinstead, 1984). The metal absorption order was found to be:



This was improved by reducing all iron from ferric to ferrous state followed by recovering both Ni and Co (Duyvesteyn et al., 2002) at pH 3.0.

Nigab et al. (1999) found that the metal absorption order was



The purification of nickel and cobalt was investigated by a number of researchers using SSX techniques. Zhang et al. (2001) reported the synergistic extraction of nickel and cobalt with a mixture of D2EHPA and LIX 860 (5-dodecyl-salicylaldoxime). The extraction of cobalt and nickel could be successfully achieved at an equilibrium pH of 3. The combination of DP-8R (di-2-ethyl-hexyl phosphoric acid, the same active component as that of D2EHPA) and Acorga M5640 (5-nonylsalicylaldoxime) was used to extract cobalt and nickel from aqueous acidic sulphate media (Cerpa and Algualcil, 2004). The extraction of over 90% of cobalt and nickel occurred at $\text{pH } 2.2 \pm 0.02$ in three stages. Both systems could not be used for purifying nickel and cobalt as the extraction pH is still high to have iron and aluminium precipitation.

To purify nickel and cobalt in the leach solution containing small amount of iron(III), aluminium and copper, another method is to extract these impurities and leave the nickel and cobalt in the raffinate. A mixed extractant system consisting of Cyanex 272 (di-2,4,4-trimethylpentyl phosphinic acid) and LIX84 (2-hydroxy-5-nonyl-acetophenone oxime) was used to purify nickel and cobalt by extraction of zinc, copper and iron from a nickel laterite re-leach solution (Cheng and Urbani, 2006; Cheng et al., 2007; Zhang et al., 2008). The addition of LIX84 to the Cyanex 272 system resulted in a pH_{50} shift of 3.5 for copper. Over 97% Cu, Zn and Fe were extracted, while the co-extractions of cobalt and nickel were less than 2.5%. The separation factor of zinc over cobalt was $>8.8 \times 10^3$ and that of copper over cobalt was $>11 \times 10^3$, suggesting an easy and complete separation of zinc, copper and iron from nickel and cobalt.

The above brief review suggests that for a leach solution containing Co^{2+} , Li^+ , Fe^{3+} , Ni^{2+} , Al^{3+} and Cu^{2+} , it is impossible to selectively extract lithium. The mixed SX or SSX systems have great potential for the separation and recovery of cobalt, nickel and lithium from spent lithium-ion leach solutions. A possible process flowsheet is to separate copper, iron and aluminium using a mixed SX system followed by further separation of nickel, cobalt and lithium by SX. In this paper, the development of a mixed solvent extractant system for the purification of cobalt and lithium will be reported.

2. Experimental

2.1. Aqueous and organic solutions

Synthetic aqueous feed solution 1 contained 16.9 g/L Co^{2+} , 3.8 g/L Li^+ , 0.6 g/L Fe^{3+} , 0.15 g/L Ni^{2+} , 0.7 g/L Al^{3+} , and 0.4 g/L Cu^{2+} . Synthetic

aqueous feed solution 2 contained 16.9 g/L Co^{2+} , 3.8 g/L Li^+ and 0.15 g/L Ni^{2+} . The solutions were prepared by dissolving the required amount of analytical grade, $\text{CuSO}_4 \cdot 5\text{H}_2\text{O}$ and $\text{Li}_2\text{SO}_4 \cdot \text{H}_2\text{O}$ and technical grade $\text{Fe}_2(\text{SO}_4)_3 \cdot x\text{H}_2\text{O}$, $\text{CoSO}_4 \cdot 7\text{H}_2\text{O}$, $\text{NiSO}_4 \cdot 6\text{H}_2\text{O}$ and $\text{Al}_2(\text{SO}_4)_3 \cdot 16\text{H}_2\text{O}$ in distilled water. Industrial grade Ionquest 801 (2-ethyl-hexyl phosphonic acid mono-2-ethylhexyl ester) was supplied by Albright Wilson Australia Limited. Acorga M5640 (5-nonylsalicylaldoxime) and Cyanex 272 were supplied by Cytec Limited. The diluent Shellsol D70 (100% aliphatic), was supplied by Shell Australia. All organic reagents were used as received without purification.

2.2. Batch test procedures

The pH isotherm tests were carried out in a one litre stainless steel vessel using Eurostar Digital overhead stirrers for mixing. The tests were conducted at room temperature ($22 \pm 1^\circ\text{C}$). The pH of the aqueous solution was measured during mixing using a ROSS Sure Flow electrode (8172BN) and a Hanna portable pH meter (HI9025). The pH of the solution mixture was adjusted by adding 12.5% (v/v) ammonia solution or 100 g/L sulphuric acid solution as required. After mixing for 5 min at the target pH, 40 mL of the solution mixture was collected at 0.5 pH intervals over the 0.5–7.0 pH range for assay.

For the determination of extraction distribution isotherms, the organic and aqueous solutions were mixed and pH adjusted as stated above. The mixing was conducted at A/O ratios of 1:2, 1:1, 2:1 and 5:1, respectively. With each A/O ratio, when the pH reached pH 4.0, and was stable for 5 min, the mixing was stopped and solution samples (40 mL) were taken for assay. For the determination of stripping distribution isotherms, the organic solution was first loaded at an A/O ratio of 2:1 and pH 4.0, and the loaded organic solution was then mixed with a stripping solution containing 80 g/L H_2SO_4 . The stripping tests were carried out at A/O ratios of 1:1, 1:2, 1:3, 1:5, 1:10, and 1:15, respectively, and after 10 min of mixing, the solution samples (40 mL) were taken for assay.

To determine extraction kinetics, the organic solution was first loaded and the volume of the 12.5% (v/v) ammonia solution used to adjust the pH 4.0 was recorded. The fresh organic solution was then mixed with the predetermined volume of the 12.5% (v/v) ammonia solution for pre-equilibration. Timing was started immediately when the pre-equilibrated organic solution was mixed with the synthetic leach solution. Solution samples (40 mL) were taken at 0.5, 1.0, 2.0, 3.0, 5.0 and 10.0 min for assay. To determine stripping kinetics, the pre-loaded organic solution pH 4.0 and a stripping solution containing 80 g/L H_2SO_4 were mixed at an A/O ratio of 1:1 and $40 \pm 1^\circ\text{C}$. Solution samples (40 mL) were taken at 0.5, 1.0, 2.0, 3.0, 5.0, and 10.0 min for assay.

2.3. Chemical analysis

From each test point, approximately 10 mL of organic solution was taken and stripped using 400 g/L sulphuric acid solution at an A/O ratio of 5:1. Approximately 10 mL of the strip liquor as well as 10 mL of the aqueous samples from each test point was taken for chemical analysis using Inductively Coupled Plasma Atomic Emission Spectroscopy (ICP-AES, Model 735-ES) by Varian Instrument Australia.

3. Results and discussions

3.1. Development of a mixed extractant system

3.1.1. Metal pH isotherms with the mixed solvent extractant system

The metal pH isotherms for feed solution 1 with an organic solution containing 7% Ionquest 801 in Shellsol D70 and a mixed organic solution containing 7% Ionquest 801 and 2% Acorga M5640 in

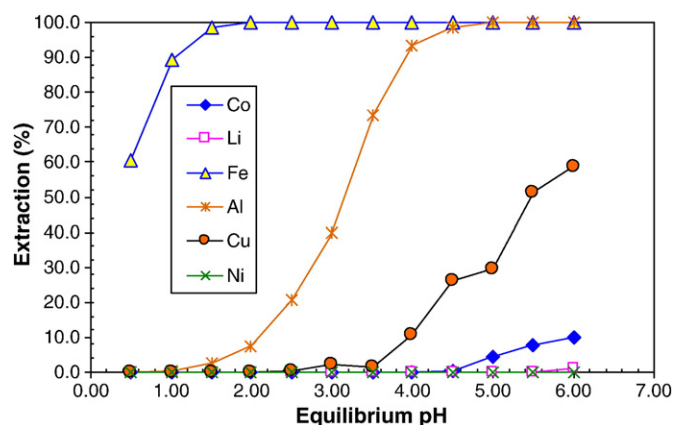


Fig. 1. Metal pH isotherms with 7% Lonquest 801 in Shellsol D70 and feed solution 1 at an A:O ratio of 2:1 and 22 °C.

Shellsol D70 are shown in Figs. 1 and 2, respectively. The metal extraction order was found to be (Fig. 1):

Fe(III) >> Al > Cu > Co, Ni, Li.

In the mixed system, the addition of 2% Acorga M5640 changed the extraction order to (Fig. 2):

Fe(III) > Cu > Al > Co, Ni, Li.

The copper extraction isotherm was shifted to a much lower pH range due to the high affinity of copper to the extractant Acorga M5640, while the extraction order of the other metals remained almost unchanged.

The metal pH_{50} values (the pH value at 50% extraction) and ΔpH_{50} values (the metal pH_{50} value difference with the organic system containing Lonquest 801 alone and the mixed organic system) are shown in Table 1. There were no pH_{50} and ΔpH_{50} values for cobalt, nickel and lithium due to their very low extractions. As discussed above, the addition of Acorga M5640 to Lonquest 801 caused a significant pH isotherm shift for copper (3.45) and had little effect on the isotherm for iron and aluminium. The Lonquest 801 system alone cannot be used for the complete separation of iron(III), copper and aluminium from cobalt, nickel and lithium due to the co-extraction of cobalt if all copper is extracted (Fig. 1). However, with the mixed organic system the copper isotherm was shifted away from that of cobalt, indicating that copper could be easily separated from cobalt, and therefore from lithium and nickel. The complete separation of iron(III), copper and aluminium from cobalt, nickel and lithium could be achieved at pH 4.0–4.5 using the mixed extractant system.

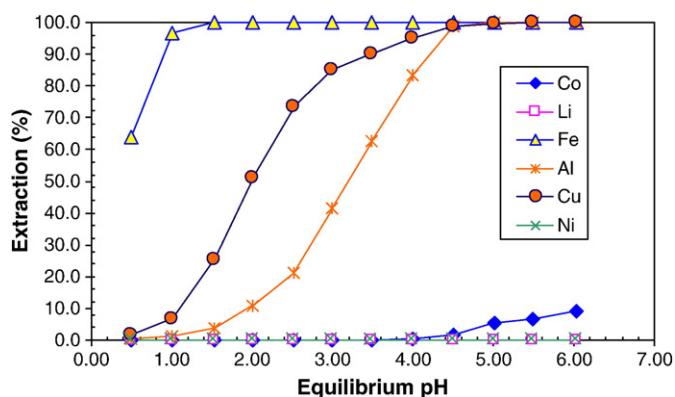


Fig. 2. Metal pH isotherms with 7% Lonquest 801 and 2% Acorga M5640 in Shellsol D70 and feed solution 1 at an A:O ratio of 2:1 and 22 °C.

Table 1

The metal pH_{50} and ΔpH_{50} values with the two organic systems and feed solution 1.

Metal	7% Lonquest 801	7% Lonquest 801 2% Acorga M5640	ΔpH_{50}
	pH_{50}	pH_{50}	
Fe(III)	<0.5	<0.5	N/A
Al	3.15	3.20	−0.05
Cu	5.45	2.00	3.45

3.1.2. Metal extraction distribution isotherms

The metal extraction distribution isotherms were determined using the mixed extractant system. The McCabe–Thiele diagram constructed for copper is shown in Fig. 3. At an A/O ratio of 2:1 and pH 4.0, three theoretical extraction stages are needed to yield a raffinate containing a few mg/L of copper. Therefore, three extraction stages are recommended for this system for the separation of iron(III), copper and aluminium from cobalt, nickel and lithium.

The metal concentrations in aqueous and organic solutions, their extractions and separation factors over cobalt at different A/O ratios are listed in Table 2. It was found that the metal extractions decreased with the increasing A/O ratios due to the limited organic capacity, although the concentrations of iron, aluminium and copper in the organic phase increased with the increasing A/O ratio. The concentration of cobalt decreased sharply with increasing A/O ratios due to the crowding effect of iron(III), copper and aluminium. The separation factor of iron increased consistently with increasing A/O ratio, which is consistent with iron having the strongest affinity to the organic system among the metals in the solution. The separation factors of aluminium and copper over cobalt increased with increasing A/O ratios up to 2:1 and decreased with further increase in A/O ratio due to the crowding effect of iron(III) when relative organic capacity was further reduced with higher A/O ratios.

3.1.3. Metal stripping distribution isotherms

The McCabe–Thiele diagram for copper stripping with a strip solution containing 80 g/L H_2SO_4 is shown in Fig. 4. It was found that two theoretical stripping stages at an A/O ratio of 1:8 were needed for copper stripping to yield a stripped organic solution containing a very low concentration of copper. It was also found that iron(III) could not be stripped effectively from the organic system with this acid solution (Table 3). For example, with an A/O ratio of 1:5, 98.7% Al and 94.5% Cu were stripped, however only 10.3% Fe(III) was stripped. It was also found that with a strip solution containing 200 g/L H_2SO_4 , iron(III) was completely stripped. This suggests that iron(III) did not poison the organic system and an organic bleed is needed with a strip solution containing higher acid concentration to strip iron(III).

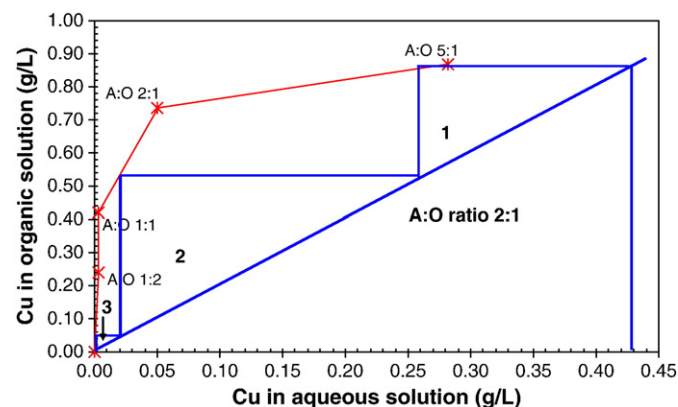


Fig. 3. Copper extraction McCabe–Thiele diagram with the mixed extractant system and feed solution 1 at pH 4.0 and 22 °C.

Table 2

Metal extractions and separation factors over cobalt at pH 4.0 with the mixed extractant system and feed solution 1 at various A/O ratios.

Element	A/O ratio	Concentration (mg/L)		Extraction (%)	Sep. factor (M/Co) ($\times 10^4$)
		Aqueous	Organic		
Fe	1:2	0	336	>99.9	1.9
	1:1	0	680	>99.9	11.1
	2:1	2	1343	99.7	58.4
	5:1	5	3280	99.3	134
	1:2	0	344	>99.9	1.9
Al	1:1	1	680	>99.8	2.2
	2:1	31	1341	95.5	3.6
	5:1	414	1397	42.0	0.7
	1:2	3	238	99.4	0.1
Cu	1:1	3	419	99.2	0.4
	2:1	50	734	88.0	1.2
	5:1	282	870	38.2	0.6
	1:2	13,362	1183	15.1	–
Co	1:1	15,781	483	3.0	–
	2:1	16,236	19	0.06	–
	5:1	16,450	8	0.01	–

3.1.4. Metal extraction kinetics

The metal extraction kinetics was determined with the mixed extractant at 22 °C (Fig. 5). About 95% of iron(III) was extracted in 2 min, indicating very fast extraction kinetics. The extraction of copper reached over 77% in 2 min, indicating reasonable fast extraction kinetics. In contrast, the extraction kinetics of aluminium was slow, with only 33% being extracted in 2 min.

An increase in temperature from 22 °C to 40 °C and an addition of 5% (v/v) TBP to the mixed extractant system were attempted to improve the extraction kinetics of aluminium. A significant increase in the extraction kinetics of aluminium was observed when the temperature was increased to 40 °C (Fig. 6 and Table 4). The aluminium extraction more than doubled in 2 min from 33% at room temperature to 72% at 40 °C, and the copper extraction was increased to 94% at 40 °C, compared to 77% at room temperature.

The addition of 5% (v/v) TBP to the mixed solvent extractant system increased the extraction kinetics of aluminium and copper to a lesser degree at room temperature (Table 4). With the addition of TBP, the aluminium extraction increased from 33% to 57%, while the copper extraction increased from 77% to 90%. Since the increase in temperature resulted in higher extraction kinetics compared to the addition of TBP, it is recommended that the separation of iron(III), copper and aluminium from cobalt, nickel and lithium be conducted at 40 °C.

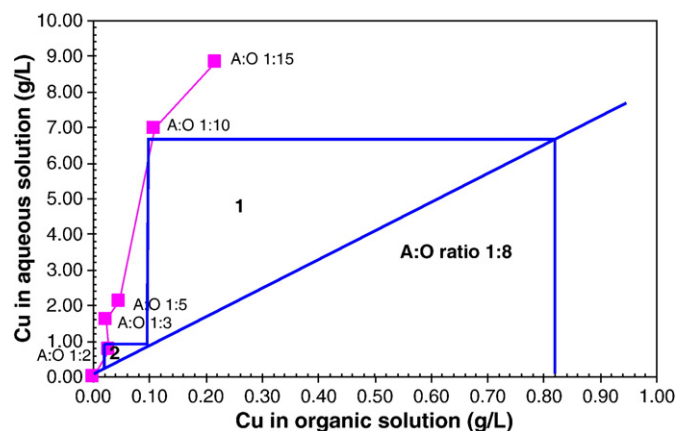


Fig. 4. Copper stripping McCabe–Thiele diagram with the mixed extractant system and a strip solution containing 80 g/L H_2SO_4 at 40 °C.

Table 3

Metal stripping from the loaded mixed extractant system with various A/O ratios at 40 °C using 80 g/L H_2SO_4 .

A/O ratio	Stripping (%)		
	Fe(III)	Al	Cu
1:2	34.3	99.0	96.5
1:3	18.3	99.5	97.1
1:5	10.3	98.7	94.5
1:10	1.2	73.6	96.8
1:15	0	56.5	73.7

3.1.5. Metal stripping kinetics

It was found that the stripping kinetics of aluminium and copper was rapid (Table 5), with 89% of aluminium and 88% of copper stripped in 2 min. However, the stripping kinetics of iron(III) was very slow with only 23% being stripped in 2 min. This, again, suggests that an organic bleed with stronger acid for iron(III) stripping is be needed.

3.1.6. Mechanism of the mixed system for copper extraction

It is proposed that in the Ionquest 801 and Acorga M5640 system, Ionquest 801 plays the role of an extractant and Acorga M5640 a synergist for copper. This is supported by the following indirect evidences:

1. The easy stripping of copper from the loaded mixed organic system. With an acid containing 80 g/L H_2SO_4 even at an A/O ratio of 1:10, over 96% Cu was stripped. In normal solvent extraction in

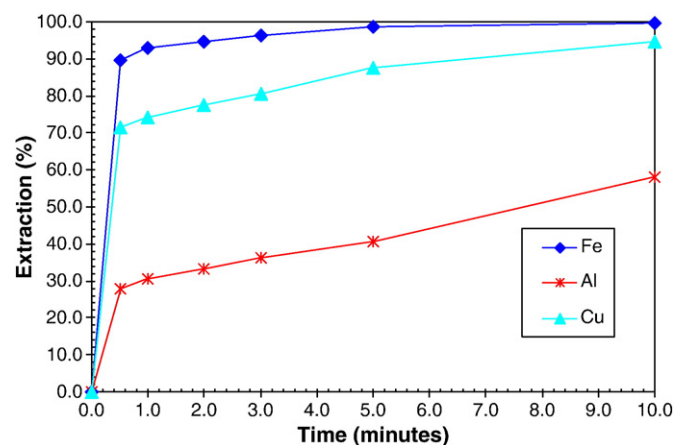


Fig. 5. Metal extraction kinetics with the mixed extractant system and feed solution 1 at an A/O ratio of 2, pH 3.75 and 22 °C.

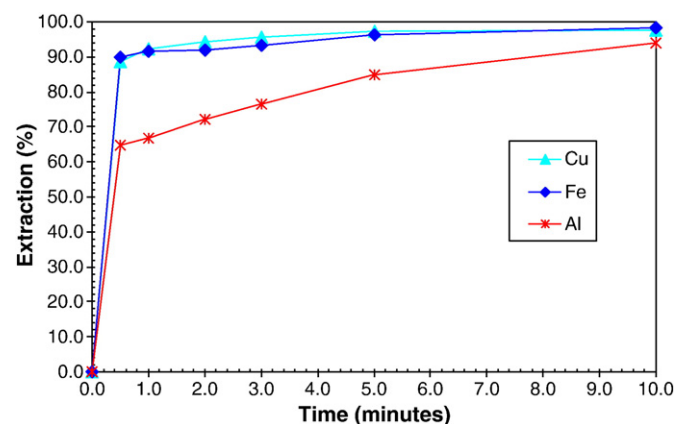


Fig. 6. Metal extraction kinetics with the mixed extractant system at an A/O ratio of 2, pH 3.92 and 40 °C.

Table 4

Copper and aluminium extractions in 2 min with the mixed extractant system and feed solution 1 under different conditions.

Metal	Extraction (%)		
	22 °C	40 °C	5% (v/v) TBP at 22 °C
Al	33.2	72.3	57.5
Cu	77.5	94.4	90.7

Table 5

Metal stripping kinetics using 80 g/L H₂SO₄ at 40 °C.

Species	Stripping (%)					
	0.5 min	1.0 min	2.0 min	3.0 min	5.0 min	10.0 min
Fe	3.7	8.0	23.5	31.3	36.1	35.5
Al	41.3	70.7	89.2	93.2	99.8	99.9
Cu	73.5	87.3	87.8	88.3	93.1	96.8

the copper industry, much higher acid concentration, for example 180 g/L H₂SO₄, is used. This is the nature of the aromatic hydroxyoxime extractant for copper.

- Metal pH isotherms with 2% Acorga 5640 in Shellsol D70 were obtained at an A/O ratio of 1:1 and 22 °C and are shown in Fig. 7. It was found that the pH₅₀ value of copper for the 2% Acorga M5640 system was 0.78. Compared with the pH₅₀ value of 2.00 for the mixed 2% Acorga M5640 and 7% Ionquest 801 system (Table 1 and Fig. 2), it suggests that if Acorga M5640 is the extractant and Ionquest 801 the synergist for copper, the copper pH₅₀ value should be lower than 0.78 due to the synergistic effect of Ionquest 801. Because Ionquest 801 is the extractant and Acorga M5640 the synergist, pH₅₀ value of copper decreased from 5.45 for system containing 7% Ionquest 801 alone to 2.00 with the addition of 2% Acorga 5640.

3.2. Cobalt, nickel and lithium purification

3.2.1. Metal pH isotherms with Cyanex 272

An organic solution containing 15% (v/v) Cyanex 272 in Shellsol D70 was tested for the further purification of cobalt, nickel and lithium after the separation of iron(III), copper and aluminium from cobalt, nickel and lithium. The metal extraction pH isotherms with the organic solution containing 15% (v/v) Cyanex 272 in Shellsol D70 and feed solution 2 are shown in Fig. 8, from which the pH₅₀ values for cobalt and nickel can be determined to be 4.35 and 7.25 respectively. The pH₅₀ of lithium is estimated to be 8.6, resulting in a $\Delta\text{pH}_{50(\text{Ni-Co})}$ of 2.9 and $\Delta\text{pH}_{50(\text{Li-Co})}$ of 4.25. The separation of cobalt from nickel and lithium can be performed at pH 5.5–6.0; at this pH, cobalt extraction

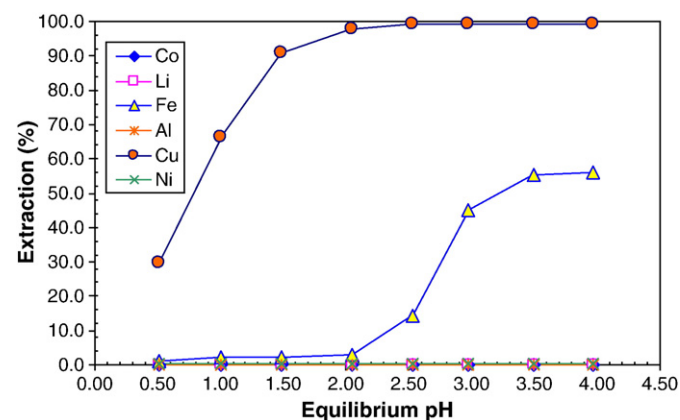


Fig. 7. Metal pH isotherms with Acorga M5640 in Shellsol D70 and feed solution 1 at an A:O ratio of 1:1 and 22 °C.

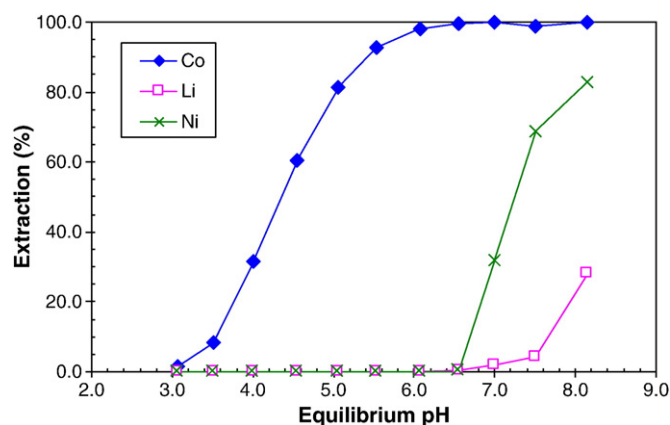


Fig. 8. Metal pH isotherms with 15% (v/v) Cyanex 272 in Shellsol D70 and feed solution 2 at an A:O ratio of 1:2 and 22 °C.

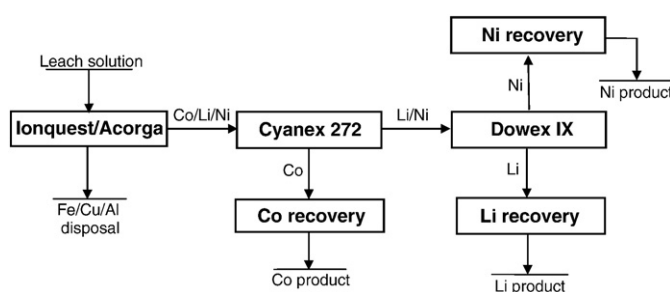


Fig. 9. A conceptual process flowsheet for the recovery of Co, Ni and Li from spent battery leach solutions.

would be greater than 90% in a single contact, whereas nickel and lithium extractions should be negligible.

3.2.2. Process flowsheet for recovery of cobalt and lithium

Based on the above data, a conceptual process flowsheet using the mixed solvent extractant system containing Ionquest 801 and Acorga M5640 and the Cyanex 272 organic system can be developed. In the first SX circuit with the mixed extractant system, all iron, aluminium, and copper would be extracted and any co-extracted cobalt, nickel and lithium would be scrubbed. The raffinate would contain only cobalt, nickel and lithium.

In the second SX circuit with Cyanex 272, cobalt can be completely separated from lithium and nickel and recovered as a pure cobalt product. An ion-exchange resin such as Dowex M4195 can then be used for the separation of nickel from lithium (Grinstead, 1984; Nagib et al., 1999; Duyvesteyn et al., 2002). Therefore, the advantage of this process is that pure cobalt, nickel and lithium products could be obtained. The conceptual process flowsheet is shown in Fig. 9.

4. Conclusions

The addition of 2% (v/v) Acorga M5640 to 7% (v/v) Ionquest 801 generated a significant pH isotherm shift for Cu, resulting in a ΔpH_{50} of 3.45. Therefore, the separation of iron(III), copper and aluminium from cobalt, nickel and lithium could be easily realised with the mixed extractant system. The McCabe–Thiele diagrams at an A/O ratio of 2:1 and pH 4.0 showed that three theoretical stages are needed for the extraction of iron, copper and aluminium. The extraction kinetics of iron(III) and copper was rapid, but the extraction kinetics of aluminium was slow. With the increase of temperature from room temperature to 40 °C, the aluminium extraction kinetics increased substantially. It is therefore recommended that the metal extraction should be carried out at 40 °C.

Based on the McCabe–Thiele diagrams, two theoretical stages are required to achieve excellent stripping of aluminium and copper at an A/O ratio of 1:8 using a strip solution containing 80 g/L H_2SO_4 . The stripping kinetics of aluminium and copper was rapid, however, iron(III) cannot be stripped effectively using 80 g/L H_2SO_4 . An organic bleed is needed to strip the iron with a strip solution containing higher acid concentration.

It is proposed that in the mixed Ionquest 801 and Acorga M5640 organic system, Ionquest 801 plays a role of extractant and Acorga M5640 a synergist for copper extraction. This is supported by the easier copper stripping and the higher copper pH_{50} value than if Acorga M5640 is used alone.

A conceptual process flowsheet was proposed for recovering cobalt, nickel and lithium from spent lithium-ion battery leach solutions using the mixed Ionquest 801 and Acorga M5640 system in the first solvent extraction circuit and Cyanex 272 in the second solvent extraction circuit. The advantage of this process is that cobalt and lithium can be effectively purified and recovered as separate products.

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